Review of the experimental evidence on pentaquarks and critical discussion

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Abstract. We review and discuss the experimental evidence on predicted baryonic states made by 4 quarks and one antiquark, called pentaquarks. Theoretical and experimental advances in the last few years led to the observation of pentaquark candidates by some experiments, however with relatively low individual significance. Other experiments did not observed those candidates. Furthermore, the masses of the $\theta^+(1540)$ candidates exhibit a large variation in different measurements. We discuss to which extend these contradicting informations may lead to a consistent picture.

1. INTRODUCTION

Pentaquarks is a name devoted to describe baryons made by 4 quarks and one antiquark. These states, predicted long time ago to exist [1, 2, 3], were searched for already in the 60'ies but few candidates found have not been confirmed [4]. Recent advances in theoretical [3] and experimental work [5] led to a number of new candidates in the last 2 years of searches [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. For recent reviews on pentaquarks see [21, 22, 23]. The current theoretical description of pentaquarks (e.g. [3, 24, 25, 26, 27, 28, 29, 30, 31]) does not lead to a unique picture on the pentaquark existence and characteristics, reflecting the complexity of the subject. In the following, we review and discuss the experimental observations of pentaquark candidates, as well as their lack of observation by some experiments.

2. EXPERIMENTAL EVIDENCE ON PENTAQUARK CANDIDATES

$\theta^+_{\bar{s}}$**:** $uudd\bar{s}$ The first observation of a candidate for the θ^+ pentaquark has been reported by the LEPS collaboration [5] in reactions $\gamma + A$ with γ energy 1.5-2.4 GeV and in the decay channel nK^+. Recent preliminary analysis of new data taken recently by LEPS lead to a confirmation of the seen peak with about 90 entries in the peak above background, as compared to 19 measured previously [32]. This first observation were followed by a number of experiments which have seen the θ^+ candidate peak [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Figure 1, left, shows the masses of all θ^+ candidate peaks measured. The θ^+ peak has been observed in two decay channels. The open points correspond to the decay channel $K^0_s p$, while the closed points to the decay channel K^+n. The candidate θ^+ peak is seen in different reactions namely of $\gamma + A$, $\nu + A$, $p + p$, $K + Xe$, $e + d$, $e + p$, $K + Xe$. All of these reactions involved at least a baryon in the initial state. The energies are small (few GeV range) for all $\gamma + A$ reactions and vary

for the rest up to $\sqrt{s}$=300 GeV for $e+p$. In the experiments measuring the decay channel K^+n the neutron was not directly measured. Even though the θ^+ candidate peak has been observed by several experiments, the individually achieved statistical significance of the signal is mostly not large. The largest significance was $S/\sqrt{B}$ = 7.8 $\pm$ 1 [8].
A remarkable observation has been made by the CLAS collaboration in the same publication [8], namely they observed that the θ^+ candidate seem to be preferably produced through the decay of a possible new narrow resonance $N^0(2400)$. A preliminary analysis of CLAS [33] showed also a second peak in the invariant mass (K^+n) at 1573 $\pm$ 5 MeV with a significance of about 6 σ. The second peak is a candidate for an excited θ^+ state which is expected to exist with about $\sim$ 50 MeV higher mass than the ground state, in agreement with the observation. A preliminary cross section estimate gives 5-12 nb for the low mass peak and 8-18 nb for the high mass peak. Cross sections have been reported also from the COSY-TOF collaboration [13] (proton beam 2.95 GeV on protons) which observed a θ^+ peak in the invariant mass pK_s^0. They measure a cross section of 0.4 $\pm$ 0.1 $\pm$ 0.1 (syst) μb which is in rough agreement with predictions of 0.1-1 μb for p+p, p+n near threshold. The ZEUS collaboration [12] (e^+p $\sqrt{s}$=300-318 GeV) is the only experiment which observed for the first time the $\overline{\theta}^-$ state decaying in $\overline{p}K_s^0$ (fig. 1, right). Most experiments measure a θ^+ width consistent with the experimental resolution, while Zeus and Hermes give a measurement of width somewhat larger than their resolution. A measurement with a much improved resolution would be important. Non-observation of θ^+ in previous experiments lead to an estimate of its width to be of the order of 1 MeV or less [34]. This limit would gain in significance, once the lack of observation of the θ^+ peak by several experiments will be better understood.

Study of the θ^+ mass variation

Figure 1, left, as previously mentioned shows a compilation of the masses of θ^+ candidate peaks observed by several experiments. The statistical and systematic errors (when given) have been added in quadrature. For GRAAL we assume an error of 5 MeV as no error has been given in [19]. For the two preliminary peaks of CLAS we assume the systematic error of 10 MeV quoted previously by CLAS. The lines indicate the mean value of the mass among the $\theta^+ \rightarrow pK_s^0$ and the $\theta^+ \rightarrow nK^+$ observations.
It appears that the mass of θ^+ from $\theta^+ \rightarrow nK^+$ observations is systematically higher than the one from $\theta^+ \rightarrow pK_s^0$ observations. This may be related to the special corrections needed for the Fermi motion and/or to details of the analysis with missing mass instead of direct measurement of the decay products.
All observations together give a mean mass of 1.533 $\pm$ 0.023 GeV and they deviate from their mean with a χ^2/DOF of 3.92. The χ^2/DOF for the deviation of the $\theta^+ \rightarrow pK_s^0$ observations from their mean of 1.529 $\pm$ 0.011 GeV is 3.76. The χ^2/DOF for the deviation of the $\theta^+ \rightarrow nK^+$ observations from their mean of 1.540 $\pm$ 0.020 GeV is 0.94.
The bad χ^2/DOF for the $\theta^+ \rightarrow pK_s^0$ observations maybe due to an underestimation of the systematic errors. In particular in some cases no systematic errors are given, sometimes because the results are preliminary. If we add a systematic error of 0.5% of the measured mass (therefore of about 8 MeV) on all measurements for which no systematic error was given by the experiments, we arrive to a χ^2/DOF for the $\theta^+ \rightarrow pK_s^0$ observations of 0.95 and a mean mass of 1.529 $\pm$ 0.022 GeV. The χ^2/DOF for the

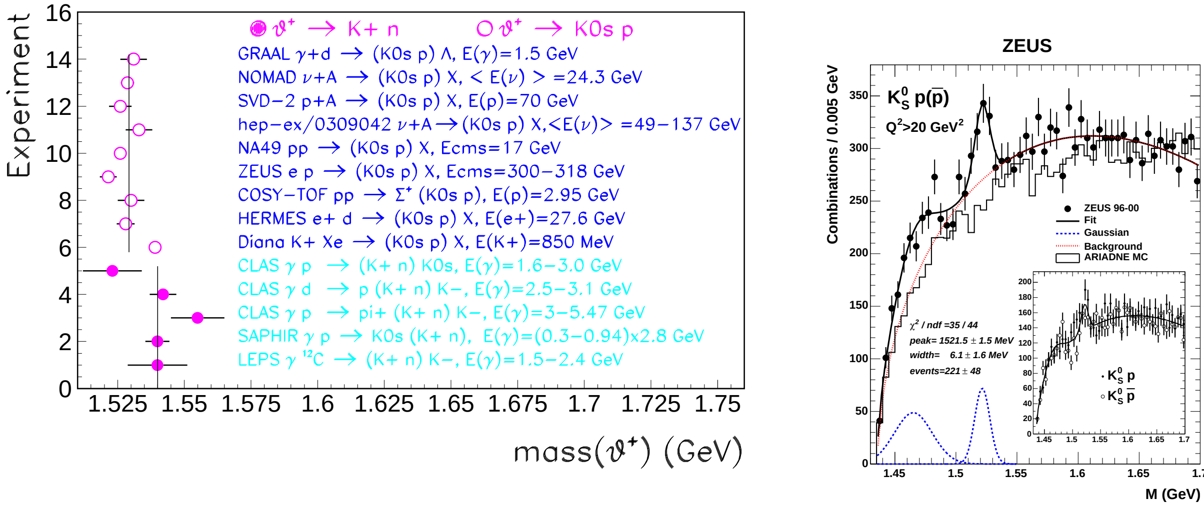

FIGURE 1. Left: Compilation of measured masses of θ^+ candidates. Right: Zeus results on the θ^+ candidate peak and its antiparticle.

$\theta^+ \rightarrow nK^+$ observations almost don't change by this, (mean mass = 1.540 $\pm$ 0.022 GeV, χ^2/DOF=0.91), because the experiments mostly give the systematic errors for this decay channel. All observations together give then a mean mass of 1.533 $\pm$ 0.031 GeV and they deviate from their mean with a χ^2/DOF of 2.1, reflecting mainly the difference of masses between the two considered decay channels. It is important to understand the origin of this discrepancy. This can be studied measuring $\theta^+ \rightarrow K^+n$ in experiments with direct detection of the neutron or the antineutron for the $\overline{\theta^-}$ like PHENIX and GRAAL.

θ^{++} A preliminary peak is quoted by CLAS [33] for the candidate $\theta^{++} \rightarrow pK^+$ produced in the reaction $\gamma p \rightarrow \theta^{++}K^- \rightarrow pK^+K^-$ at 1579 $\pm$ 5 MeV. A previous peak observed by CLAS in the invariant mass pK^+ has been dismissed as due to ϕ and hyperon resonance reflexion [35]. The STAR collaboration quoted a preliminary peak in the pK^+ and $\overline{p}K^-$ invariant masses at 1.530 GeV in d+Au collisions at $\sqrt{s}$=200 GeV [36].

Ξ, N^0 The NA49 experiment has observed in p+p reactions at $\sqrt{s}$=17 GeV the pentaquark candidates $\Xi^{--}(1862 \pm 2MeV) \rightarrow \Xi^-\pi^-$, the $\Xi^0(1864 \pm 5MeV) \rightarrow \Xi^-\pi^+$ and their antiparticles [15]. They measure a width consistent with their resolution of about 18 MeV. They also observe preliminary results of the decay $\Xi^-(1850) \rightarrow \Xi^0(1530)\pi^-$ with simarly narrow width as the other candidates [16].

The experiment STAR has shown preliminary results on a N^0 ($udsd\overline{s}$) or Ξ ($udss\overline{d}$) I=1/2 candidate [18]. STAR uses minimum bias Au+Au collisions at $\sqrt{s}$=200 geV and observes a peak in the decay channel ΛK^0_s at a mass 1734 $\pm$ 0.5 (stat) $\pm$ 5 (syst) MeV with width consistent with the experimental resolution of about 6 MeV and $S/\sqrt{B}$ between 3 and 6 depending on the method used [18].

The GRAAL experiment has shown preliminary results on two narrow N^0 candidates. One candidate is observed at a mass of 1670 MeV in the invariant mass of ηn from the

reaction $\gamma d \to \eta n X$. The neutron has been directly detected. The other is observed at a mass of 1727 MeV in the invariant masses of ΛK_s^0 as well as in the invariant masses of $\Sigma^- K^+$ at the same mass and with the same width [20]. The second reaction allow to establish the strange quark content and therefore to exclude the Ξ hypothesis. The difference of 7 MeV between the STAR and GRAAL measured masses of 1727 and 1734 MeV, should be compared to the systematic errors. STAR quotes a systematic error of 5 MeV while GRAAL quotes no systematic error.
The mass of the peaks at 1670 and at (1727,1734) MeV is in good agreement with the N masses suggested by Arndt et al [37]. In this paper a modified Partial Wave analysis allows to search for narrow states and presents two candidate N masses, 1680 and/or 1730 MeV with width below 30 MeV.

$\theta_{\overline{c}}^0$ The H1 collaboration at DESY used $e^- p$ collisions at $\sqrt{s}$=300 and 320 GeV and have observed a peak in the invariant masses $D^{*-}p$ and $D^{*+}\overline{p}$ at a mass 3099 $\pm$ 3 (stat) $\pm$ 5 (syst) MeV and width of 12 $\pm$ 3 MeV [17]. This peak is a candidate for the state $\theta_{\overline{c}}^0$ = $uudd\overline{c}$ and is the first charmed pentaquark candidate seen.

Lack of observation of pentaquark candidates

Several experiments have reported preliminary or final results on the non-observation of pentaquarks e.g. e^+e^-: Babar, Belle, Bes, LEP experiments, $p\overline{p}$: CDF, D0 pA:E690, γp: FOCUS, pA: HERA-B, ep: Zeus (for the θ_c^0) μ^+ ^6LiD: COMPASS, Hadronic Z decays: LEP, π, K, p on A: HyperCP, $\gamma\gamma$: L3, π, p, Σ on p: SELEX, pA: SPHINX, $\Sigma^- A$: WA89 $K^+ p$: LASS, [38]. HERMES has reported the non-observation of a θ^{++} candidate peak in the pK^+ invariant masses [10]. No other experiment has observed the candidates for the Ξ and the θ_c pentaquarks seen by NA49 and H1. Especially Zeus has searched for the θ_c under similar conditions as H1 and with similar statistics, without observing a peak [39]. Many of the experiments reporting non observation of pentaquarks have a very high statistics and good mass resolution.
It has been argued that the non-observation of pentaquark states in the above experiments could be due to an additional strong suppression factor for pentaquark production in e^+e^- collisions, as well as in B decays which is lifted in reactions like γA in which a baryon is present in the initial state [40]. The constituents of the θ^+ are already present in the initial state of e.g. low energy photoproduction experiments, while in other experiments baryon number and strangeness must be created from gluons [40]. It is important to try to assess the expected cross sections.
The non observation of pentaquarks in high energy interactions of hadrons (CDF ($p\overline{p}$), E690 (pA) etc) can be a consequence of the decrease of the pentaquark cross section with increasing energy [41, 42]. This depends however on the kinematic region considered, and it is suggested to look for pentaquarks in the central rapidity region [41, 42].
In addition, if the θ^+ is produced preferably through the decay of a new resonance $N^0(2400) \to \theta^+ K^-$ as suggested by CLAS and NA49 and as discussed in [40, 43], neglecting this aspect maybe a further cause of its non-observation in some experiments.
Some authors pointed out the importance to exclude kinematic reflexions as reason behind the θ^+ peak [44]. This known source of systematic errors is under investigation by the experiments which observe pentaquark candidates.
It is clear that a higher statistic is desirable in order to confirm the pentaquark observations reported so far. New data taken in 2004 and planned to be taken in 2005 will

lead to enhancements in statistics of experiments up to a factor of 15 allowing to test the statistical significance and make more systematic studies. Experiments searching for pentaquarks should test also the production mechanisms proposed in the literature e.g. the θ^+ production through the $N^0(2400)$ decay. For example Phenix could search for the final state $\overline{\theta^-}K^+$ or $\overline{\theta^-}K_s^0$ demanding the invariant mass of $\overline{\theta^-}K_s^0$ and $\overline{\theta^-}K^+$ to be in the range 2.3 to 2.5 GeV, and study the option to trigger online on this channel.

3. SUMMARY AND CONCLUSIONS

Recent theoretical and experimental advances led to the observation of candidates for a number of pentaquarks states. In particular candidate signals have been observed for the $\theta^+(1533)$, θ^{++}(1530/1579), θ_c^0(3099), $\Xi^{--}(1862)$, $\Xi^0(1864)$, $\Xi^-(1850)$, $N/\Xi^0(1734/1727)$, $N^0(2400)$, $N^0(1670)$ states as well as a possible excited $\theta_{\bar{s}}^+(1573)$ state. These observations are promising, however despite the large number of e.g. the $\theta_{\bar{s}}^+$ observations, they all suffer from a low individual statistical significance. A much higher statistics is needed to support and solidify the existing evidence. Several other high statistics experiments have reported lack of observation of those candidates. The inconsistency among experiments waits to be clarified through high statistics measurements of pentaquark candidates, their characteristics (cross sections, quantum numbers) and upper limits in the case of non-observation. Furthermore, systematic studies are needed as well as advanced theoretical understanding of the observations, in particular of the narrow width and the production mechanism of the observed candidates as well as the possible reasons behind their non-observations by some experiments. Combined theoretical and experimental efforts should be able to answer soon the question if pentaquarks exist.

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